Photonic LO signal generation and distribution techniques for VLBI and an Artificial Calibration Source for ALMA high-site

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Contents

- MZM-LS (Alternative scheme LS with ML)
- Alternative scheme Line Length Corrector
- Artificial Calibration Source (CW and Noise)
A bit of Phase noise  
(Allan variance)

\[ L_c = \omega_o^2 \left[ \frac{\alpha_p}{6} + \frac{\alpha_f}{12} T + \frac{\sigma_y^2}{57} T^2 \right] \]

- \( L_c \): the loss of coherence,
- \( \omega_o \): the angular frequency of local oscillator,
- \( \alpha_p \): the Allan variance \( ((\text{standard deviation})^2) \) of white phase noise at 1 sec,
- \( \alpha_f \): the Allan variance \( ((\text{standard deviation})^2) \) of white frequency noise at 1 sec,
- \( \sigma_y^2 \): the constant Allan variance \( ((\text{standard deviation})^2) \) of flicker frequency noise,
- \( T \): the integration time [sec].

Coherence loss of White PM is independent of time

by Rogers, Moran and Kawaguchi

The phase noise of the LO system should be in White PM noise.
Try and imagine the ALMA interferometer with unstable photonic LO.

ALMA will not be an interferometer but a 66 single-dish-antenna array.

Q1. Is current photonic LO system stable enough for Band-11 (Band-10, -9) and/or VLBI applications? where Photonic LO system consists ML, LS, and LLC.

If it is not stable enough, ALMA will not be an interferometer.

The phase stability and estimated coherence loss;

σy(1)=1E-13 (in white PM): 938GHz: 5.8% loss
2E-13 (in white PM): 938GHz: 23.2% loss
1E-13 (in flicker FM): 263GHz: 43.1% loss @30sec
Q2. ALMA is a connected interferometer array?

ALMA can be considered a connected interferometer in short baseline (about 1 km). It means the LO noise is the common noise. Fringes will be able to be obtained with no LLC. This is similar situation to SMA which has no LLC.

But in long baseline, LLC stability which we have to keep in mind..

Q3. How about high frequency?

It becomes difficult to consider ALMA to be connected interferometer

The target phase stability of the transmission signal

\[ \sigma_y(1)=1E-13 \text{ (in White PM)} \]

938 GHz: 5.8% loss
263 GHz: 0.5% loss
1. Photonic LO signal generator

MZM-LS

Microwave signal is generated as a difference frequency of two light-waves
Photonic LO signal generator

The Photonic signal generators can be classified as follows.

(1) Optical phase locked loop scheme (Baseline ML, LS)

(2) Optical modulation scheme (MZM-LS)
Schematic of Optical Phase Locked Loop ML and LS

- From Reference Laser (ML)
- Optical spectrum
- Optical spectrum
- Optical spectrum
- Slave Laser
- Coupler
- Photo mixer
- Harmonic mixer
- Microwave signal
- Amp.

→ phase stability depends on the reference laser stability
→ Complex: high running/maintaining cost
→ Susceptible to external disturbances
Proposed Photonic signal generator: MZM-LS
LiNbO$_3$ high-extinction ratio Mach-Zehnder optical modulator

Optical phase of each arm is controlled by applying DC bias.

This scheme is more stable than the microwave multiplier method.

→ phase stability is independent of the reference laser stability
→ Simple: low running/maintaining cost
→ Robust to external disturbances
→ High-speed frequency switching
Measured phase stability:
Phase noise has characteristic of White-PM noise.

Coherence loss is less than 0.71% @ 500GHz.
Time error: 17.3 fs (short), 5.5 fs (long)
The prototype MZM-LS was developed by NAOJ. And the production level MZM-LS has been delivered to NRAO by ASIAA as the fruit of the collaborative research project between NAOJ and SIAA. A COTS ML is inside. But it has not been exported to Chile yet.
This technique will also bring a significant running cost reduction.

This technique has been applied to

NAOJ Holography Receiver

Artificial Calibration Source
2. Optical transmission signal stabilizer

Alternative scheme LLC (ALLC)

ALLC is not authorized yet.

Microwave signal transmission is performed in the form of frequency difference between two coherent light waves.
The transmission signal phase become unstable when the fiber is swaying.

This is not fiber length change but Chromatic dispersion cased by external disturbances (Pressure, Vibration, Acoustic noise, Bending, Twist and Temperature change).

Optical fiber has a differential group delay (DGD) on each wavelength which is not stable in time.

This effect causes chromatic dispersion.

Does LLC have a compensation capability of Chromatic Dispersion?
Microwave signal transmission in the form of frequency difference between two coherent light waves

Input optical signals

\[ \begin{align*}
\lambda_1 \\
\lambda_2
\end{align*} \]

Refractive Index: \( n(\lambda) \)

Single mode fiber

Input pulse

\( \lambda \)

Output pulse

Time spread of a transmitted pulse

Round-trip phase measurement on \( \lambda_1 \)

Transmission LO

Differential phase is detected by photo-mixer

Optical round-trip path length depend on Refractive Index \( n(\lambda) \) and CD \( (\lambda) \): chromatic dispersion

Round-trip phase on \( \lambda_2 \) is different from \( \lambda_1 \)

The independent round-trip phase measurement of two light waves is indispensable.
Frequency switching issue
Round-trip phase measurement is done on one optical signal ($\lambda_1$)

During frequency switching, LLC cannot detect the transmission LO phase change!!??

When the frequency switching mode, $\lambda_2$ and $\lambda_3$ are no sensitive region for LLC.

The independent round-trip phase measurement of two light waves is indispensable.

Round-trip phase measurement on $\lambda_1$
Transmission LO
Differential phase is detected by photo-mixer $\lambda_1-\lambda_2$ or $\lambda_1-\lambda_3$

Time spread of a transmitted pulse

Frequency switching issue
When the frequency switching mode, $\lambda_2$ and $\lambda_3$ are no sensitive region for LLC.

The independent round-trip phase measurement of two light waves is indispensable.
Dual difference phase measurement method

Under the effect of Chromatic Dispersion (CD), the transmission line lengths (the length of the signal path in the optical fiber cable) are different between the two coherent optical signals.

At Antenna: For $\lambda_1$: $(\varphi_1/2)$: m is even or $[(\varphi_1/2) + \pi]$: m is odd,
For $\lambda_2$, $[(\varphi_2/2) + \Phi]$: n is even or $[(\varphi_2/2) + \pi + \Phi]$: n is odd.

Photo-mixer output: $(\varphi_1/2) - [(\varphi_2/2) + \Phi]$ or $(\varphi_1/2) - [(\varphi_2/2) + \Phi] + \pi$

When we adjust the round-trip phases to equal by using PLL;

$\varphi_1 = \varphi_2 + 2\Phi$

If this equation is established by controlling the phase $\Phi$, the Photo-mixer output phase becomes 0 or $\pi$.

which can compensate an influence of a transmission line as a constant value.
Real-time phase stabilizer

Forward and return signals are distinguished by frequency and polarization.
The transmission delay in the correlation result can be compensated in off-line processing by using the measured short-term round trip phase.
Measured phase stability using post-processing method:

80 GHz transmission via a 10 km SM fiber and a 5 km fiber

- Transmission signal
- Compensation (Post processing)

Allan standard deviation

Integration time in seconds

Measured phase stability using post-processing method
3. Artificial calibration source
It is proposed that we place a small low-powered millimeter-wave source on one of the mountain peaks overlooking the ALMA operations site. This will serve several purposes:

(1) to provide a signal for interferometric holography measurements of the antenna surfaces

(2) to provide a source of known and preferably changeable polarization so we can measure the polarization properties of the antennas

(3) to provide a source with high signal-to-noise ratio to help measure things like coherence, phase stability, switching times and perhaps stability and sideband ratio.

The requirements taken from Richard Hills memo
Installation location

Location of the planned communications tower
A Block diagram of the Artificial Source on the ALMA Site (final form)

Antenna site
- Band3 W-band UTC-PD
- J-Band UTC-PD
- Wire Grid
- Wire Grid with rotator

Ground site
- Narrow Line-width Fiber Laser
- MZM-LS
- Optical Comb generator
- Synthesizer
- Rubidium osc.
- Optical Switch
- ASE Source
- EDFA
- Optical Switch & combiner
- AWG
- SMF cable

65-400GHz

Stage-II Development items

ASE: Amplified spontaneous emission
AWG: Arrayed waveguide grating
Performance

1. Signal type
   CW and Noise
2. Frequency coverage (two horn)
   Band-3: 67-125 GHz (spec: 84-116 GHz)
   Band-6/7: 211-373 GHz
3. Frequency accuracy
   Band-3: 8 mHz (spec: <1kHz)
   Band-6/7: <1 kHz
4. Transmitter power to antenna
   -30 dBm
5. Transmitter beam width
   50 deg.
6. Noise power density
   -121 dBm/Hz (spec: -135 dBm/Hz)
7. Polarization
   Linear
8. Polarization rotation angle
   +/- 45 deg.
9. Polarization rotation accuracy
   0.002 deg. (spec: 0.5 deg.)
10. Polarization extinction ratio
    >38 dB (spec: > 30 dB)
With the Band-3 cartridge
According to *Artificial Source: Measurements at the OSF with an ALMA Front End* by R.Hills

It is to be emphasized that we are not relying on the change in amplitude with angle being exactly what is predicted in order to use the source to calibrate ALMA’s calibration properties. This should give us an absolute calibration of the orientation of the planes of polarization for ALMA with an accuracy of +/- 1 degree.